SOUND MECHANISMS OF BRASS INSTRUMENTS, LAST TWENTY YEARS RESULTS.

PACS REFERENCE 43.75-Fg

Joël GILBERT
Laboratoire d'Acoustique de l'Université du Maine - UMR CNRS 6613
Av. Olivier Messiaen,
72085 Le Mans Cedex 9
France
Tel: 33+(0)243833283
Fax: 33+(0)243833520
E-mail: Joel.Gilbert @univ-lemans.fr

ABSTRACT

Due to the huge advances in computer power during the last twenty years, there has been a big increase in numerical simulations in musical acoustics. Since the major contribution in the paper of Elliot and Bowsher (1982) dealing with "regeneration in brass wind instruments", there have been some noticeable improvements in brass instrument modelling. First, the "brassy sounds" have been clearly demonstrated to be a consequence of non-linear propagation inside the bore. Second, due to mechanical measurements coming from recently developed artificial mouths, some progress in the understanding of the vibrating or "buzzing" lips has been achieved.

INTRODUCTION

Brass and reed instruments are acoustic sources using a valve effect. The acoustic oscillation is a result of the destabilisation of a mechanical element - the reed of the clarinet or lips of the trombone player - whose movement changes the input cross-section of the instrument. This destabilisation is the result of a complex aeroelastic coupling between (1) the mecahnical element, (2) the air flow entering the instrument as a result of the static overpressure in the mouth of the musician, and (3) the instrument itself (the acoustic resonator). After the pioneering works of Helmholtz (1860), a lot of research has been carried out on wind instruments, including brass instruments, until a major contribution of Elliot and Bowsher (1982) in their paper entittled "regeneration in brass wind instruments".

From the last twenty years, a renewal of interest in brass acoustics has occured and some noticeable improvements in brass instrument modelling have been achieved. The paper is divided into two parts. After a brief introduction, we present most of the works concerning brass instruments which have appeared during the last twenty years. Firstly, the works linked with the acoustical resonator, the instrument itself, are presented (section two). The input impedance measurement and calculations are compared to a high degree of accuracy in Causse et al (1984), but there are some remaining discrepancies due to the plane wave hypothesis simplifications. That has been partly overcome by taking into account higher modes in the sound field description. Furthermore, following Beauchamps (1980) suggestion, it has recently been proven that the linear acoustic approximation is not valid when describing high amplitude sounds. It has been clearly shown that “brassy sounds” are the immediate consequence of non linear propagation in the bore. Secondly, the works linked with the vibrating lips are presented (section three). Following the pioneering work of Martin (1942), several studies have been performed on vibrating lips recorded on video. The major barrier to understanding the behaviour of the vibrating lips is due to difficulties in comparing theories with experimental results coming from in vivo experiments. This has been partially overcome with measurements done using recently developed artificial mouths.

BRASS INSTRUMENTS, FROM INPUT IMPEDANCE TO NON LINEAR PROPAGATION

Input impedance

It is well known that reed and brass instruments generate periodic oscillations whose fundamental frequency is close to one of the resonance frequencies of the bore. Many studies have been carried out to get very accurate measurements and theories of input impedances of bores, from which the resonance frequencies are extracted. Among others, the papers of Backus (1976), Pratt et al (1977) show input impedance curves of brass instruments. Causse et al (1984) have compared calculated and measured input impedance curves to a high degree of accuracy. The calculations are based on linear acoustic theory assuming plane wave propagation inside the bore (low frequency hypothesis). The input data of the calculations are geometrical measurements of the internal bore profile of the instruments in question. In the nineties, software developed for research activities was adapted for instrument manufacturers (Resonans ; Kausel et al, 2001). The theoretical backgrounds are sufficiently accurate to be used as a tool for aiding design of wind instruments, in order to improve the intonation for example. The input impedance is a physical quantity defined in the frequency domain. Frequency domain is useful because of the intuitive link between resonance frequency and pitch of the corresponding note played. Measurements and calculations can be done in the time domain as well getting impulse responses. Throughout the nineties the pulse reflectance technique was developed showing that the bore profile can be reconstructed from the input impulse response of the tube. This technique has been applied first in the medical field (Fredberg et al, 1980 ; Marshall, 1990), and then in musical acoustics (Watson and Bowsher, 1988). For the purpose of comparison of bore profile between brass instruments, bore reconstructions of the accuracy now possible offer a useful tool for the taxonomist. Myers (1998) did a systematic study comparing the reconstructed bores of a lot of brass instruments from different periods (from renaissance to modern period).

The flare of a trombone bell increcases very rapidly toward the end. In such a case the plane-wave approximation is not a good one. Amir et al (1997) have developed a multi-modal analysis in order to improve the plane-wave theoretical results. Then they have calculated the input impedance of a trombone bell taking into account more than just the first mode (plane-wave approximation). The comparison with the measured input impedance improves when extra modes are taken into account. As an illustration, some results applied to a trumpet bell are displayed in figure 1. The discrepancies due to the plane-wave approximation are negligible around the second resonance (230 Hz), and 15 Hz around the eighth resonance (930 Hz) ; taking into account more modes than the plane wave mode implies a decrease of the resonance frequencies. Extra modes have been recently taken into account in time domain methods as well to improve the pulse reflectometry method (Kemp et al, 2001).

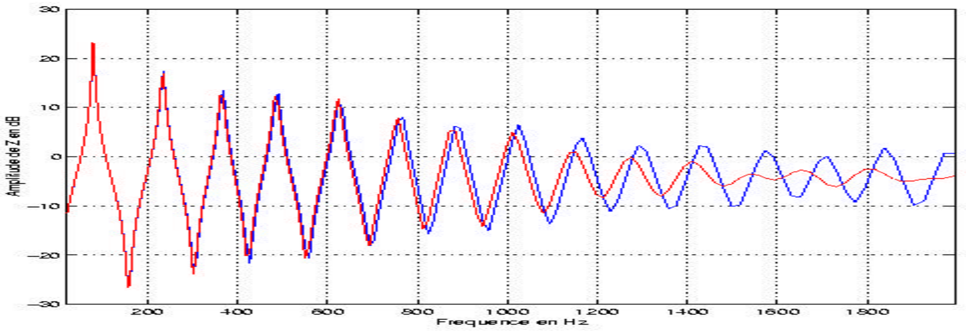

Figure 1 : Calculated input impedance curves of a trumpet using one mode (plane wave mode only) and using two modes (magnitude in dB as a function of frequency in Hz).

Non linear propagation and “brassy sounds”

As stated above, wind instruments can be represented by input impedances based on linear acoustic model. Beauchamp (1980) proposed that strong non-linear effects could appear in brass instruments when they are played loudly. According to the internal acoustical pressures measured in a trombone mouthpiece by Elliot and Bowsher (1982), a theoretical critical distance of shock wave formation can be estimated. A first approximation shows quickly that strong nonlinear effects as shock wave formation can appear in the trombone slide, and this has been verified experimentally by Hirschberg et al (1996).

Because nonlinear propagation effects are cumulative, the resulting distorsion of the signal can be spectacular, leading to the formation of shock waves in the instrument, especially when the tube is at its maximum extension (figure 2). In such a case, one can say that a trombone player is able to generate four hundred sonic booms per second (Gilbert and Petiot, 1997). From the musical point of view, the “brassy sounds” are the immediate consequence of non linear propagation in the bore. Msallam et al (2000) have reproduced the generation of brassy sounds for loud tones with synthesis based on nonlinear wave propagation in the bore. The first level of modelling (no nonlinear effects) accounts well for the existence of periodic regimes, and even for more complex regimes of oscillation, and as such it provides a reasonable basis for discussion of small oscillations. As mentionned by Msallam, these solutions can be the input data for the “nonlinear resonator black box”. In the so called “extrinsic nonlinear model”, the self-sustained acoustic pressure solution is first obtained from a classic model (resonator characterised by a linear reflection function). This solution is then used as an incoming wave of a nonlinear resonator (the slide of the trombone, cylindrical part of the resonator) which transmits a distorted wave at the end of the tube, which is then propagated in the bell and radiated outside following the linear acoustic approximation.

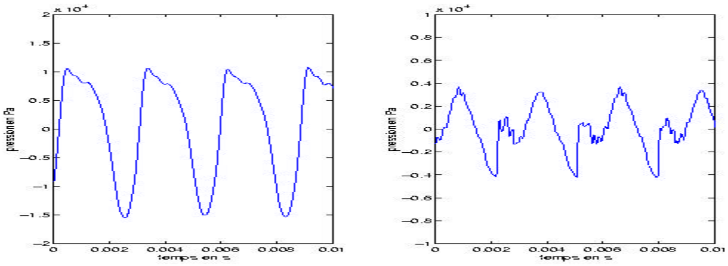

Figure 2 : Acoustic pressure (in Pa) as a function of time (in s) measured in the mouthpiece (left) and at the exit of the slide section of a trombone (right) for a fortissimo level ; the microphone separation is 2.8 m corresponding to the 6^{th} position of the slide (F3 played, 345 Hz).

VIBRATING LIPS, FROM REAL TO ARTIFICIAL “BUZZING LIPS”

The complete modelling of wind instruments requires the description of the instrument itself (see recent developments about the acoustic resonator above), the description of the exciting system (the reed of the clarinet or the lips of the trombonist) and the modeling of the aeroelastic coupling between the two induced by the flow of air into the instrument. Single reed instruments have been extensively studied, both theoretically and experimentally (see for example Hirschberg et al, 1995), giving convincing explanations of their behaviour from small to large oscillations, but some questions concerning lip-reed instruments remain open. The lips are flexural continuous structures submitted to aerodynamic forces with boundary conditions imposed by the mouthpiece, which can not be easily reduced to a simple model, such as the simple second order mechanical oscillator used for single reed instruments.

Following the pioneering work of Martin (1942), several authors like Copley and Strong (1996) have obtained detailed photographic sequences and lip motion data on which lip models for brass instruments may be more accurately based. Lip motion was observed from the front and side for several notes from low to high pitch, and with many players from beginners to experts. These kind of results are very useful from the pedagogical point of view for musicians (observation of embouchures, upper lip to lower lip ratio). Detailed numerical values for lip area, height, and width are published, and then available for comparisons with lumped models based on simulations. These lumped mechanical models need parameters such as resonance frequencies and quality factors, and getting them from in vivo experiments is a very difficult task. This is where artificial mouth set-ups come in.

Usefullness of artificial mouth to get mechanical responses

Several single-reed artificial mouths have been designed by many authors (Backus, 1963 ; Wilson and Beavers, 1974 ; Dalmont et al, 1995), but brass artificial mouths are more recent. The major advantage of the artificial mouth is its ability to keep stable during a long time without any psychological feedback. The mechanical responses of these artificial lips have been measured (Gilbert et al, 1998) as a function of embouchure. Several measurements for different embouchures have been done, with the main control parameters of the embouchure being the mechanical pressure of the mouthpiece on the lips, the water pressure inside the latex tubes representing the lips, and the static mouth pressure. A typical mechanical response such as those obtained by Cullen et al (2000) is displayed figure 3.

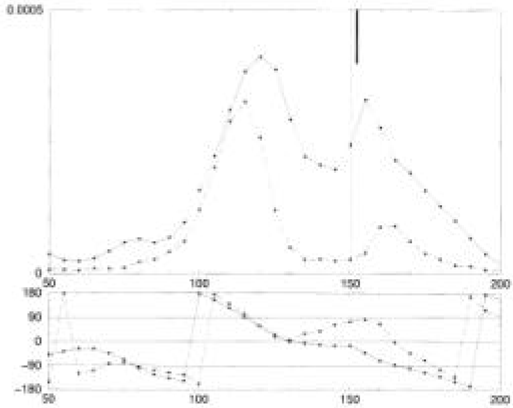

Figure 3 : A measured mechanical response of artificial lip reed with (top curve) and without flow (magnitude, and phase as a function of frequency in Hz) ; the playing frequency just above threshold and the acoustic resonance of the pipe is marked on the graph as a short thick vertical line and a dotted line respectively.

The mechanical response curve exhibits several resonances, one of the two major ones being destabilised when the mouth pressure reaches a threshold value. The two resonances respond with different phases, described by Helmholtz, the first one behaves in an "outward striking" way, the second behaves in an "inward striking" way (see Cullen et al, 2000).

Behaviour in threshold, toward a 2-mass model

The easiest way to study the self-sustained oscillations of wind instruments is to begin with the linear stability analysis of the equilibrium position of the reed or the lips for a given mouth pressure. The basic model, which has to be linearised around the equilibrium position, is based on a system of two coupled oscillators. One oscillator corresponds to the acoustical resonance of the instrument around which the acoustic oscillation grows. The second oscillator corresponds to one flexural mode of the mechanical valve (reed or lips). The two oscillators being coupled by the inflow coming from the mouth of the player can be destabilised around their equilibrium position at a given threshold mouth pressure, where a threshold playing frequency can be defined (roughly speaking the threshold note corresponds to pianissimo playing). One major conclusion of the linear stability analysis technique is the following (Fletcher, 1979) : if the mechanical valve is acting in an "inward striking" way, the threshold frequency is below the two resonance frequencies, the acoustical one and the mechanical one. Conversely, if the mechanical valve is acting in an "outward striking" way the threshold frequency is above the two resonance frequencies. This has been verified in woodwind like instruments (see for example Fletcher and Rossing, 1990). As assumed by Helmholtz, it has been verified that the single-reed instruments behave in an "inward-striking way" (see for example Dalmont et al, 1995). Helmholtz assumed that brass instruments behave in an "outward-striking way", but experiments do not reach such a definitive conclusion.

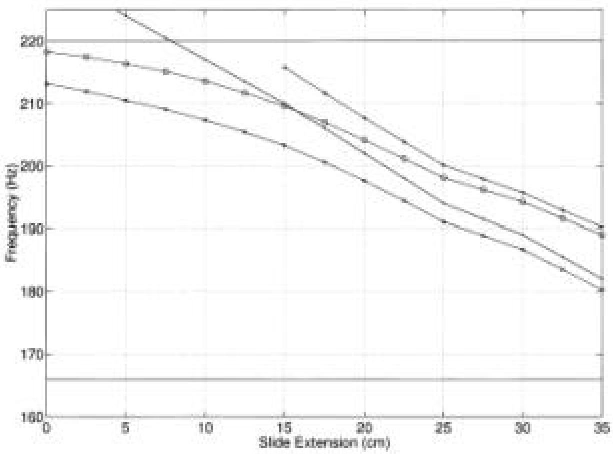

Figure 4 : Variation of the threshold frequency with slide extension, the measured values (o) are surrounded by two simulated values obtained from "outward striking" (+) and "inward striking" (x) one-mass model ; the acoustical resonance frequencies of the pipe and the two mechanical resonance frequencies of the lip reed are displayed.

Several authors (Yoshikawa, 1995 ; Chen and Weinreich, 1996) tried to conclude by comparing threshold frequencies with the two resonance frequencies. Yoshikawa's major conclusion was that lower notes have tendency to favour the outward striking reed type, whereas the highest notes have tendency to favour the inward striking reed. Chen and Weinreich's conclusion is a bit different : the playing frequency under normal playing conditions (the "most comfortable note") is almost always higher than the corresponding air column resonance, supporting "outward striking reed" behavior. But they did find that with some efforts the players can generate playing frequencies both lower and higher than the corresponding air column resonance. Extensive measurements of threshold frequencies and resonance frequencies for a given oscillation regime (Cullen et al, 2000) obtained from artificial mouth measurements have suggested a behaviour which passes smoothly from "inward striking" to "outward striking" character as the trombone slide is extended (figure 4) or the embouchure parameters changed.
Then it seems unlikely that this type of behaviour can be explained using a lip model with only a single degree of freedom. Recent measured threshold frequencies have been successfully compared with numerical results coming from a preliminary two-mass model. In that study, following the models of the vocal folds, a system of two coupled mechanical oscillators has been implemented and their parameters supplied by the pair of mechanical resonances extracted from measured mechanical responses (figure 3). Furthermore, this kind of two-mass model can generate self-sustained oscillations without the need of acoustical feedback, and can explain the ability of players to get their lips vibrating without the instrument ("the buzzing technique" used by players to warm up before playing).

CONCLUSION AND FURTHER WORK

As shown above, many interesting acoustical studies applied to brass instruments have been published since the eighties, symbolized by the paper of Elliot and Bowsher (1982), until today, but obviously the study of the acoustic behaviour of brass instruments has to carry on. The recent experimental results obtained with artificial mouths are very promising and will provide new insights into describing the motion of real players lips. The fundamental behaviour of the buzzing lips near threshold is becoming more understandable. A new step will be taken when simulations of lip motion coming from 2-mass models is successfully compared with motion analysed from artificial mouths.

As said in the abstract, the advances in computer power during the last twenty years have resulted in a big increase in numerical simulations in musical acoustics. Actually, many brass sound syntheses have been done with a high degree of audio realism (Strong and Dudley, 1993 ; Dietz and Amir, 1995 ; Adachi and Sato, 1996 ; Msallam et al, 2000 ; Vergez and Rodet, 2000), even if most of them are based on crude one-mass model of lips. The progress of understanding coupling between the vibrating lips and brass instrument is crucial for development of efficient instrument design tools. In parallel, an alternative use of the artificial mouth technology to science is an adaptation for manufacturers as a testing ground (Gilbert et al, 2002).

Beyond today's understanding, there are some open questions still. For instance one can suggest general questions like the effect of the mouth cavity resonator (very noticeable in didjeridoo playing for example), or the consequences of wall vibrations on brass behaviour (comparison between welded or connected brasses). The up to date models are able to get realistic oscillation regimes, and even multiphonic regimes coming from modulated mouth pressures by singing, but the "pedal note" regime described by Bouasse (1930) and well known by players is not understood by the physicists.

Aknowledgments

The author would like to express gratitude to Jean-Francois Petiot, Jean-Pierre Dalmont, Sylvie Ponthus and Franck Teissier, Mico Hirschberg and Regis Msallam, Murray Campbell, John Cullen, Mark Neal, Orlando Richards and Arnold Myers for their efficient collaboration in trying to understand acoustic of brass instruments.

References

Adachi, S., Sato, M. (1996). "Trumpet sound simulation using a two-dimensional lip vibration model", J. Acoust. Soc. Am. 99, 1200-1209.

Amir, N., Pagneux, V., Kergomard, J. (1997). "A study of wave propagation in varying cross-section waveguides by modal decomposition", J. Acoust. Soc. Am. 101, 2504-2517.

Backus, J. (1963). "Small-vibration theory of the clarinet", J. Acoust. Soc. Am. 35, 305-313.

Backus, J. (1976). "Input impedance curves for the brass instruments", J. Acoust. Soc. Am. 60, 470-480.

Beauchamp, J.W. (1980). "Analysis of simultaneous mouthpiece and output waveforms", Audio Engineering Society, preprint No. 1626, 1-11.

Bouasse, H. (1930). "Instruments à vent ", librairie Delagrave, Paris. Reprint by Blanchard edition, 1986.

Caussé, R., Kergomard, J., Lurton, X. (1984). "Input impedance of brass musical Instruments - Comparison between experiment and numerical models", J. Acoust. Soc. Am. 75, 241-254.

Chen, F.C., Weinreich, G. (1996). "Nature of the lip reed", J. Acoust. Soc. Am. 99, 1227-1233.

Copley, D.C., Strong, W.J. (1996). "A stroboscopic study of lip vibrations in a trombone", J. Acoust. Soc. Am. 99, 1219-226.

Cullen, J., Gilbert, J., Campbell, M. (2000). “Brass instruments : linear stability analysis and experiments with an artificial mouth”, Acustica 86, 704-724.

Dalmont, J.P., Gazengel, B., Gilbert, J., Kergomard, J. (1995). "Some aspects of tuning an clean intonation in read instruments", Applied Acoustics 46, 19-60.

Dietz, P., Amir, N. (1995). "Synthesis of trumpet tones by physical modeling", Proceedings of the International Symposium on Musical Acoustics, 471-477.

Elliot, S.J., Bowsher, J.M. (1982). "Regeneration in brass wind instruments", Journal of Sound and Vibration 83, 181-217.

Fletcher, N.H. (1979). "Excitation mechanisms in woodwind and brass instruments", Acustica 43, 63-72.

Fletcher, N.H., Rossing, T.D. (1990). “The physics of musical instruments”, Springer-Verlag, New York.

Fredberg, J.J., Wohl, M.E.B., Glass, G.M., Dorkin, H.L. (1980). “Airway area by acoustic reflections measured at the mouth”, J. Appl Physiol. 48, pp. 749-758.

Gilbert, J., Petiot, J.F. (1997). "Brass instruments, some theoretical and experimental results", Proceedings of ISMA'97, Institute of Acoustics, Vol. 19, 391-400.

Gilbert, J., Ponthus, S., Petiot, J.F. (1998). “Artificial buzzing lips and brass instruments : experimental results”, J. Acoust. Soc. Am. 104, 1627-1632.

Gilbert, J., Teissier, F., Petiot, J.F., Campbell, M. (2002). “Analyse comparative d’instruments à vent de type cuivre à partir d’une bouche artificielle”, Procedings of the 6th French Conference on Acoustics, Lille, France. To be published.

Helmholtz, H. (1860). "On the sensation of tone ". Reprint by Dover edition, New-York, 1954.

Hirschberg, A., Gilbert, J., Msallam, R., Wijnands, A.P.J. (1996). "Shock waves in trombones", J. Acoust. Soc. Am. 99, 1754-1758.

Hirschberg, A., Kergomard, J., Weinreich, G. (1995). "Mechanics of musical instruments", CISM courses and lectures no. 355, Springer-Verlag, Wien.

Kausel, W., Anglmayer, P., Widholm, G. (2001). “A computer programm for optimisation of brass instruments. Part I. Concept, implementation”. Acustica / Acta Acustica 85, S77 (1999).

Kemp, J.A., Amir, A., Campbell, D.M., van Walstijn, M. (2001). “Multimodal propagation in acoustic horns”. Proceedings of the International Symposium on Musical Acoustics. Musical sounds from past millennia. Edited by D. Bonsi, D. Gonzalez, D. Stanzial. 521-524.

Marshall, I. (1990). ”The production of acoustic impulses in air”, Meas. Sci. Technol. 1, 413-448.

Martin, D.W. (1942). "Lip vibrations in a cornet mouthpiece", J. Acoust. Soc. Am. 13, 305-308.

Msallam, R., Dequidt, S., Caussé, R., Tassart, S. (2000). “Physical model of the trombone including non linear effects, application to the sound synthesis of loud tones”, Acustica 86, 725-736.

Myers, A. (1998). “Characterization and taxonomy of historic brass musical instruments from an acoustical standpoint”, Ph. D. of the University of Edinburgh, United Kingdom.

Pratt, R.L., Elliott, S.J., Bowsher, J.M. (1977). "The measurement of the acoustic impedance of brass instruments", Acustica 38, 236-246.

Resonans. Software for wind-instrument design. Developed at the Laboratoire d’Acoustique de l’Université du Maine (Le Mans, France) in collaboration with IRCAM (Paris, France).

Strong, W.J., Dudley, J.D. (1993). "Simulation of a player-trumpet system", Proceedings of the Stockholm Music Acoustics Conference, 520-524.

Vergez, C., Rodet, X. (2000). “Dynamical Systems and physical models of trumpet-like instruments. Analytical study and asymptotical properties”, Acustica 86, 147-162.

Watson, A.P., Bowsher, J.M. (1988). “Impulse measurements on brass musical instruments”, Acustica 66, 171-174.

Wilson, T.A., Beavers, G.S. (1974). "Operating modes of the clarinet", J. Acoust. Soc. Am. 56, 653-658.

Yoshikawa, S. (1995). "Acoustical behavior of brass player's lips", J. Acoust. Soc. Am. 97, 1929-1939.